

Onset of Deconfinement and Critical Point: NA49 and NA61/SHINE at the CERN SPS

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Abstract. This paper is dedicated to the memory of József Zimányi one of the founders of the experiment NA49 at the CERN SPS. Firstly, the paper summarizes the main results of NA49 concerning observation of the onset of deconfinement in central Pb+Pb collisions at the low SPS energies. Secondly, it sketches the physics program of NA61 at the CERN SPS, the successor of NA49, which in particular aims to discover the critical point of strongly interacting matter. Finally, a brief review of the future experimental programs in the CERN SPS energy range is given.

1 Introduction

The primary motivation and the basic aim of the study of nucleus-nucleus collisions at high energies is to uncover properties of the phase diagram of strongly interacting matter in the domain of transition between hadron gas and quark gluon plasma (QGP) [1]. In this effort a particular role was and is played by the experimental programs at the CERN SPS. They started in the mid 80s with the study of collisions induced by O and S beams at the top SPS energy (200A GeV). Two predicted signals [2,3] of QGP creation in A+A collisions were observed. These were the enhanced production of strange hadrons [4] and the suppressed production of J/ψ mesons [5]. A long-lasting dispute continues whether these are specific for the QGP creation. In 1996 the Pb ions were accelerated in SPS for the first time and Pb+Pb interactions at 158A GeV were registered by the second generation of heavy ion experiments, which included the NA49 experiment. Soon after that the energy scan program at the SPS begun and central Pb+Pb collisions at 20A, 30A 40A and 80A GeV were collected over the years 1999-2002. This search was motivated by the prediction of [6] that the onset of deconfinement should lead to a steepening of the increase of the pion yield with collision energy and to a sharp maximum in the energy dependence of the strangeness to pion ratio. The onset was expected to occur at approximately 30A GeV [6]. In parallel to the study at the SPS CERN the corresponding programs were performed at lower (AGS BNL) and higher (RHIC BNL) energies. The basic results from this world-wide experimental effort are already published. They confirm the prediction that the onset of deconfinement is located at the low SPS energies [7,8] and motivate further studies of nucleus-nucleus collisions in the SPS energy range. The new experimental programs are planned at the SPS CERN [9], RHIC BNL [10], NICA JINR [11] and SIS-300 FAIR [12]. In particular, the experiment NA61/SHINE (SHINE = SPS Heavy Ion and Neutrino Experiment) at the SPS CERN, which is based on the NA49 experimental facility, aims to discover the critical point of the strongly interacting matter and study in detail the properties of the onset of deconfinement [13]. These goals can be reached by performing a pioneering two-dimensional scan in collision and size of colliding nuclei.

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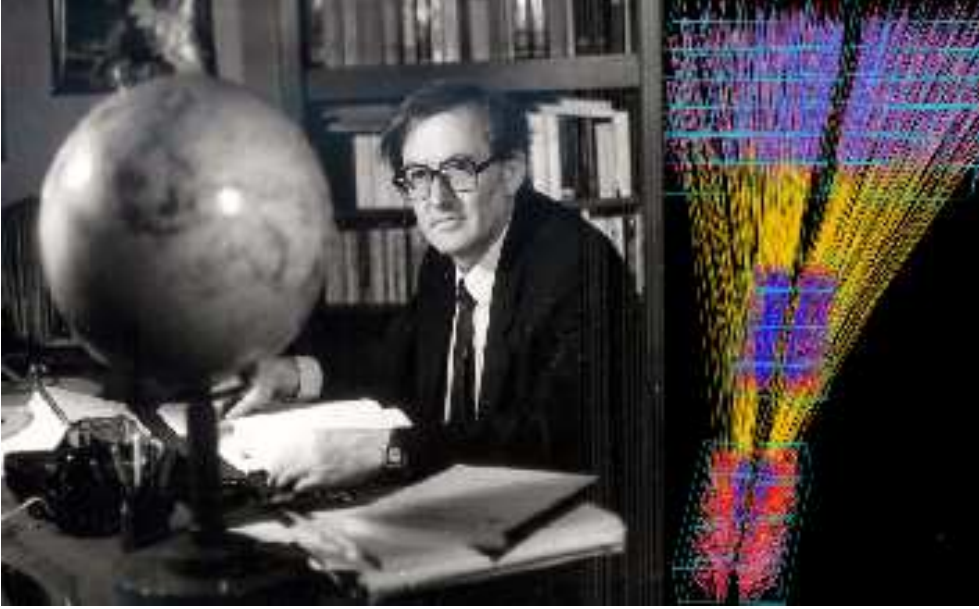


Fig. 1. József Zimányi (1931-2006)

József Zimányi (Fig. 1) was one of the founders of NA49 and thus one of the grand-fathers of NA61/SHINE. His deep interest in physics of strongly interacting matter guided his theoretical, experimental and organizational activities. In particular, József Zimányi

- established a strong scientific and financial participation of the Budapest group in NA49,
- strongly supported the heavy ion program at CERN and
- is a co-author of about 100 NA49 papers published in the period between 1995-2007.

Last, but not least, his enthusiasm and work motivated all of us.

2 Onset of Deconfinement and NA49

Figure 2 shows a sketch of the phase diagram of strongly interacting matter in the temperature and baryon chemical potential (T, μ_B) plane as suggested by QCD-based considerations [14,15]. The main feature is the existence of two phases of matter: the hadron gas at low (T, μ_B) values and quark gluon plasma at high T and/or μ_B values. The characteristic features of QGP is a large specific entropy caused by the activation of the color degrees of freedom and a reduction of threshold effects caused by low masses of u , d and s quarks as well as gluons in comparison to masses of hadrons. Thus the transition to QGP (the onset of deconfinement) is predicted [6] to be signaled by an increased entropy production (the kink in energy dependence of pion multiplicity, see Fig. 3) and a reduction of the threshold effects related to the particle masses (the horn in K^+/π^+ ratio, see Fig. 4). With increasing collision energy the temperature of the matter created at the early stage of nucleus-nucleus collisions increases. At sufficiently high energy the early stage T is expected to reach the domain of the transition between hadron gas and QGP. This situation is depicted in Fig. 2 (left). The NA49 energy scan program resulted in an observation of the effects predicted for the onset of deconfinement, the kink and the horn, in central Pb+Pb (Au+Au) collisions at the low SPS energies. The most recent data are shown in Figs. 3 and 4 [8].

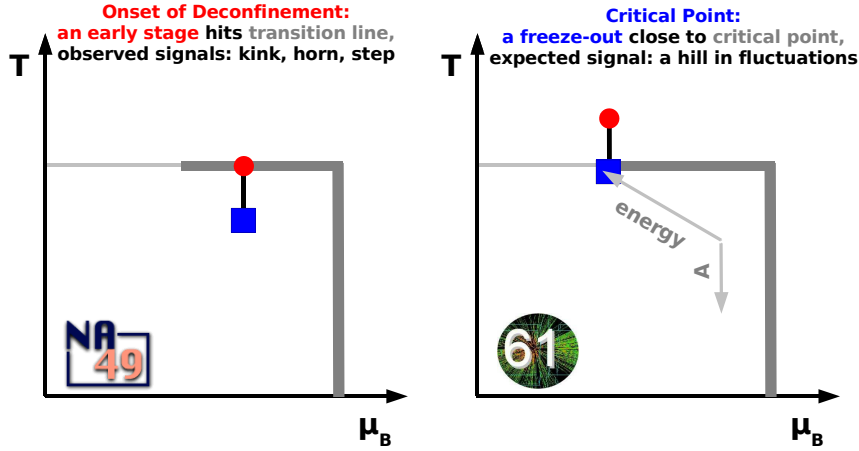


Fig. 2. The sketch of the phase diagram of strongly interacting matter with the indicated parameters of the matter created in nucleus-nucleus collisions at the early stage (circles) and at the freeze-out (squares). The first order transition region between the hadron gas and QGP is shown by the thick lines, whereas the cross-over region by the thin lines. Left: The early stage parameters hit the transition region, the onset of deconfinement is observed. Right: The freeze-out parameters hit the end point of the first order transition region, the critical point is observed.

3 Critical Point and NA61

To a large extent the QCD predictions are qualitative, as QCD phenomenology at finite temperature and baryon number is one of the least explored domains of the theory. More quantitative results come from lattice QCD calculations which can be performed at $\mu_B = 0$. They suggest a rapid crossover from the hadron gas to the QGP at the temperature $T_C = 170 - 190$ MeV [16,17], which seems to be somewhat higher than the chemical freeze-out temperatures of central Pb+Pb collisions ($T = 150 - 170$ MeV) [18] at the top SPS and RHIC energies.

The nature of the transition to QGP is expected to change with increasing baryon chemical potential. At high potential the transition may be of the first order (marked by the thick line in Fig. 2) with the end point of the first order transition domain, being the critical point of the second order. The rapid cross-over is expected at low μ_B values (marked by the thin line in Fig. 2). A characteristic property of the second order phase transition is a divergence of the susceptibilities. Consequently an important signal of a second-order phase transition at the critical point are large fluctuations, in particular an enhancement of fluctuations of multiplicity and transverse momentum are predicted [19].

Thus when scanning the phase diagram a maximum of fluctuations located in a domain close to the critical point (the increase of fluctuations can be expected over a region $\Delta T \approx 15$ MeV and $\Delta\mu_B \approx 50$ MeV [20]) or the critical line should signal the second order phase transition. The position of the critical region is uncertain, but the best theoretical estimates based on lattice QCD calculations locate it at $T \approx 158$ MeV and $\mu_B \approx 360$ MeV [21,22]. It is thus in the vicinity of the chemical freeze-out points of central Pb+Pb collisions at the CERN SPS energies [18].

Pilot data on interactions of light nuclei (Si+Si, C+C and p+p) taken by NA49 at 40A and 158A GeV indicate that the freeze-out temperature increases with decreasing mass number, A , of the colliding nuclei [18]. This means that a scan in the collision energy and mass of the colliding nuclei allows us to scan the (T, μ_B) plane in a search for the critical point (line) of strongly interacting matter [19].

The experimental search for the critical point by investigating nuclear collisions is justified at energies higher than the energy of the onset of deconfinement. Only at these energies the freeze-out point has a chance to be close to the critical point (see Fig. 2 for an illustration). The

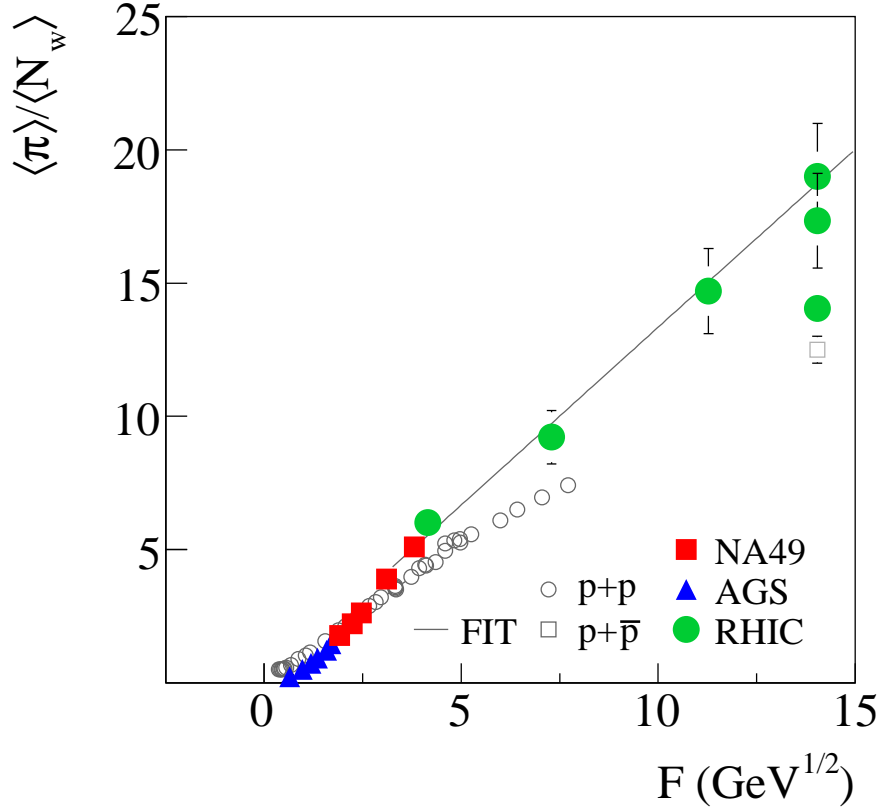


Fig. 3. Energy dependence ($F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}$) of the mean pion multiplicity per wounded nucleon measured in central Pb+Pb and Au+Au collisions (full symbols), compared to the corresponding results from $p + p$ reactions (open circles) [8]. The slope of the dependence for heavy ion collisions increase by about 1.3 at the low SPS energies (the kink).

effects related to the onset of deconfinement are measured at 30A GeV ($\sqrt{s_{NN}} \approx 8$ GeV) (see Figs. 3 and 4). This limits a search for the critical point to an energy range $E_{lab} > 30A$ GeV ($\mu_B(CP) < \mu_B(30A \text{ GeV})$).

The search for the critical point and the study of the properties of deconfinement require a comprehensive energy scan in the whole SPS energy range (10A-158A GeV) with light and intermediate mass nuclei. The NA61/SHINE collaboration [9] intends to register p+p, C+C, S+S and In+In collisions as well as p+Pb interactions at 10A, 20A, 30A, 40A, 80A, 158A GeV and a typical number of recorded central events per reaction and energy of $2 \cdot 10^6$. The expected NA61/SHINE data are compared with the data registered by NA49 in Fig. 5.

In order to demonstrate that the selected set of data covers the phase diagram region relevant for the search for the critical point the hypothetical positions of the chemical freeze-out points for central In+In, S+S and C+C collisions (full dots from bottom to top) at 158A, 80A, 40A, 30A, 20A and 10A GeV (full dots from left to right) are shown in Fig. 6 (right). These positions are calculated using a parametrization [18] of the dependence of T and μ_B on collision energy and system size based on the existing data. These data are shown in Fig. 6 (right) by the open squares. The upper open and the corresponding full dots indicate the upper limit of the temperature obtained for p+p interactions. Note that for these collisions the grand canonical

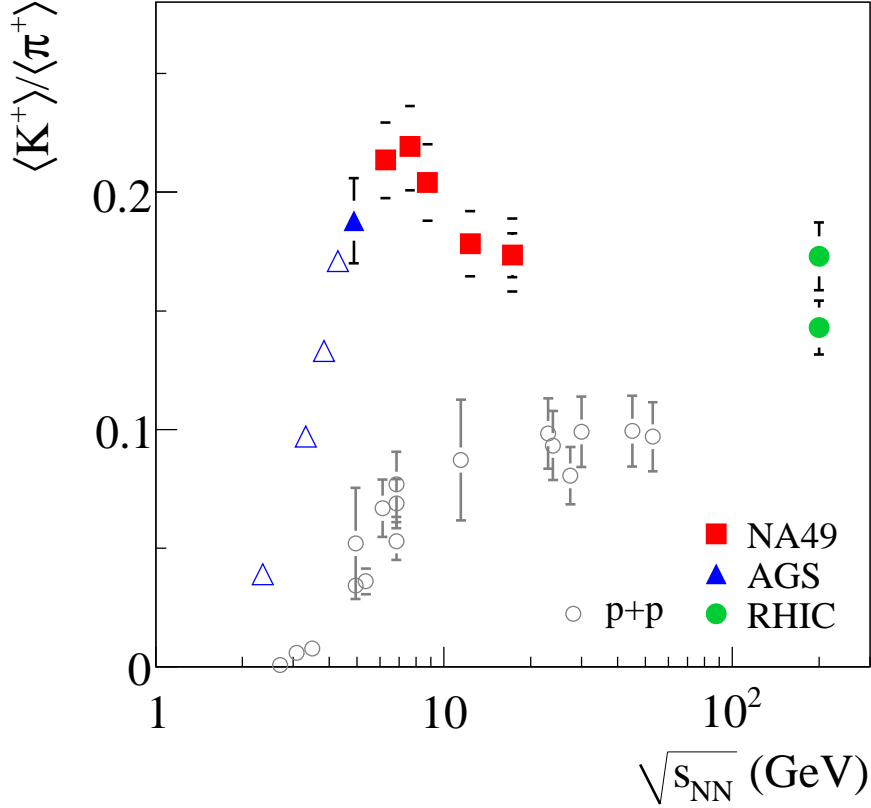


Fig. 4. Energy dependence of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio measured in central Pb+Pb and Au+Au collisions (full symbols) compared to the corresponding results from $p + p$ reactions (open circles) [8]. The dependence for heavy ion collisions features a non-monotonic dependence with a maximum at the low SPS energies (the horn).

approximation is not valid and thus baryon-chemical potential and temperature are not well defined. The lower solid line shows the parametrization for the central Pb+Pb collisions.

The NA61 physics program goes significantly beyond the search for the critical point [9]. The full program consists of:

- measurements of hadron production in nucleus-nucleus collisions, in particular fluctuations and long range correlations, with the aim to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter,
- measurements of hadron production in proton-proton and proton-nucleus interactions needed as reference data for better understanding of nucleus-nucleus reactions; in particular correlations, fluctuations and high transverse momenta will be the focus of this study,
- measurements of hadron production in hadron-nucleus interactions needed for neutrino (T2K) and cosmic-ray experiments (Pierre Auger Observatory and KASCADE).

The NA61 beam request which follows from the proposed program is given in Table 1. The 2007 run is already performed and its summary can be found in [23]. The preparations for the 2008 run are in progress.

As discussed above the nucleus-nucleus program has the potential for an important discovery – the experimental observation of the critical point of strongly interacting matter. Within

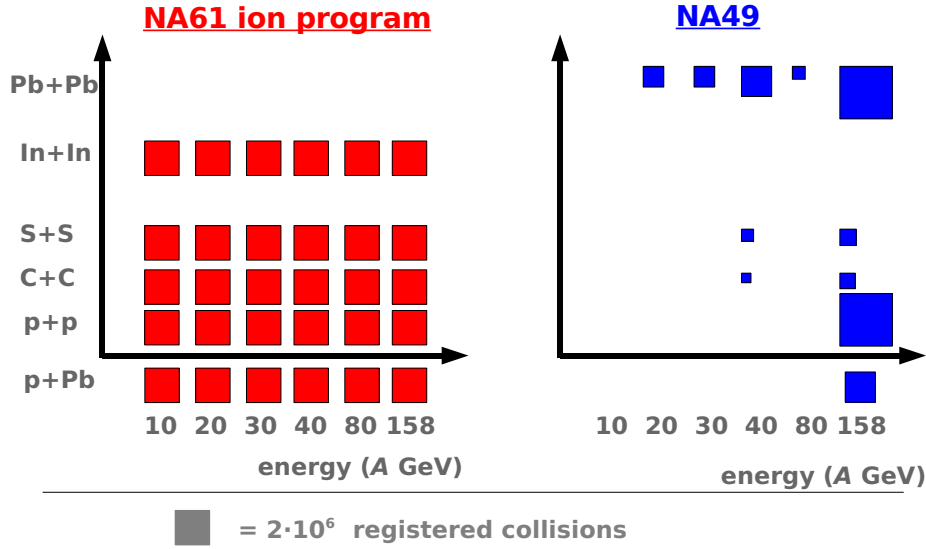


Fig. 5. Left: The data sets planned to be registered by NA61 in the ion program. Right: The data sets registered by NA49.

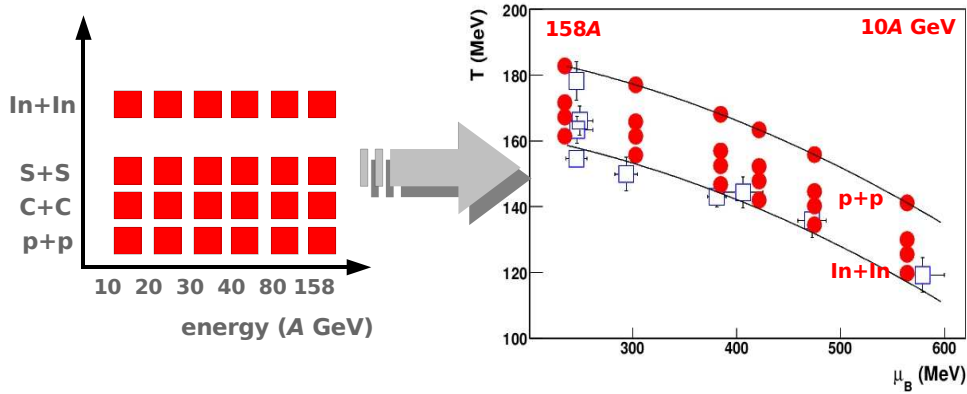


Fig. 6. Left: The data sets on central A+A collisions planned to be registered by NA61 in a search for the critical point of strongly interacting matter and a study of the properties of the onset of deconfinement. Right: Hypothetical positions of the chemical freeze-out points of the reactions (In+In, S+S, C+C and p+p from bottom to top at 158A, 80A, 40A, 30A, 20A and 10A GeV from left to right) to be studied by NA61 in the (temperature)-(baryon-chemical potential) plane are shown by full dots. The open squares show the existing NA49 data.

Beam	Energy (A GeV)	Year	Days	Physics	Status
p	30	2007	30	Data for T2K, C-R, R&D	<i>performed</i>
p	30, 40, 50	2008	14	Data for T2K, C-R	<i>approved</i>
π^-	158, 350	2008	3	Data for C-R	<i>approved</i>
p	158	2008	28	High p_T	<i>approved</i>
S	10, 20, 30, 40, 80, 158	2009	30	CP&OD	<i>recommended</i>
p	10, 20, 30, 40, 80, 158	2009	30	CP&OD	<i>recommended</i>
In	10, 20, 30, 40, 80, 158	2010	30	CP&OD	<i>to be discussed</i>
p	158	2010	30	High p_T	<i>to be discussed</i>
C	10, 20, 30, 40, 80, 158	2011	30	CP&OD	<i>to be discussed</i>
p	10, 20, 30, 40, 80, 158	2011	30	CP&OD	<i>to be discussed</i>

Table 1. The NA61 beam request. The following abbreviations are used for the physics goals of the data taking: CP - Critical Point, OD - Onset of Deconfinement, C-R - Cosmic Rays.

this program NA61 intends to carry out for the first time in the history of heavy ion collisions a comprehensive scan in two dimensional parameter space: size of colliding nuclei versus interaction energy. Other proposed studies belong to the class of precision measurements.

NA61 shall perform these measurements by use of the upgraded NA49 apparatus [24]. The most essential upgrades are an increase of an event rate by a factor of 10 and the construction of a projectile spectator detector which will improve the accuracy of determination of the number of projectile spectators by a factor of about 20. The cost of all upgrades and detector maintenance is estimated to be 2 MCHF. Synergy of different physics programs as well as the use of the existing accelerator chain and detectors offer the unique opportunity to reach the ambitious physics goals in a very efficient and cost effective way.

4 Future experiments at the CERN SPS energies

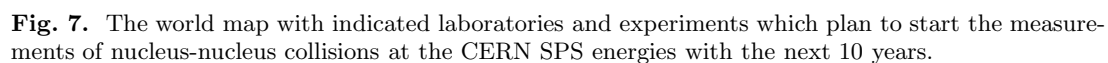
The exciting and reach physics which can be studied in nucleus-nucleus collisions at the CERN SPS energies motivates physicists from BNL, JINR and FAIR to perform experimental studies which should complement the CERN SPS programs. Fig. 7 shows the world map with indicated laboratories and experiments which plan to start measurements of nucleus-nucleus collisions at the CERN SPS energies within the next 10 years.

Two fixed target programs (CERN SPS [9] and FAIR SIS-300 [12]) and two programs with ion colliders (BNL RHIC [10] and JINR NICA [11]) are foreseen. The basic parameters of the future programs are summarized in Fig. 8. The SPS and RHIC energy range covers energies significantly below and significantly above the energy of the onset of deconfinement ($\approx 30A$ GeV in the fixed target mode). Thus these machines are well suited for the study of the properties of the onset of deconfinement and the search for the critical point. The top energies of NICA and SIS-300 are just above the energy of the onset of deconfinement. The physics at these machines shall then focus on the study of the properties of the dense confined matter close to the transition to QGP. This is illustrated in Fig. 9 which shows a location of the new programs in the baryon chemical potential together with the existing data and physics benchmarks.

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CP – critical point
OD – onset of deconfinement, mixed phase, 1st order *PT*
HDM – hadrons in dense matter

Fig. 8. The main parameters of the experimental programs of study nucleus-nucleus collisions at the CERN SPS energy range within the next 10 years.

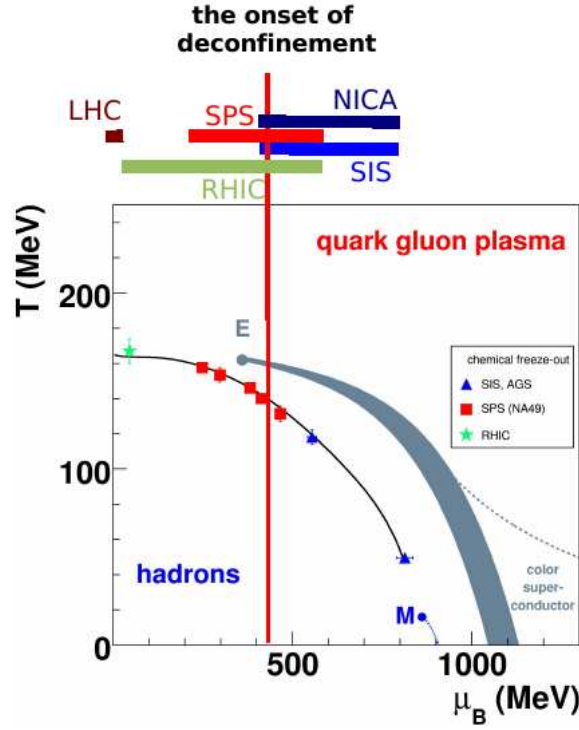


Fig. 9. The phase diagram of strongly interacting matter with indicated chemical freeze-out points of central Pb+Pb (Au+Au) collisions at different energies, and baryon-chemical potential ranges covered by the future programs.

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